Ventilation as a Dynamical Problem.

I WILL begin by calling attention to a few points of special and fundamental importance.

I.—Inlets and Outlets.

The first point is concerned with the numerical relation between the volume of air flowing through the room to be ventilated, and the motive power which maintains the flow. I need hardly repeat that steady ventilation requires openings for air to come in, openings for air to go out, and motive power to keep a steady current flowing through these openings. The motive power I shall call the "head" or "aeromotive force," and shall suppose it to be estimated by the number of foot-pounds of work required to get a pound weight of air into the room and out again in the course of the ventilation. The mode of estimation is a complicated one, but "head" is also equivalent to pressure-difference, a more familiar idea, and "aëromotive force" is selected on the analogy of "electro-motive force" for special reasons that will appear later. Be the names good or bad, the head is closely related to the horse-power spent in maintaining the ventilation current. If, for example, 5 h.p. are being spent, causing a current of air measured at 100 cubic ft. per second, the head is $\frac{5 \times 550 \times 12 \cdot 8}{100}$ or 352 ft., equivalent to about 5 inches of water pressure.

The "head," or "aëromotive force," for ventilation may arise in three ways—from wind, from shafts carrying warm air, and from fans or blowing machines. The first source of power for ventilation purposes is called natural, the second may be called thermal, and the third mechanical. The "natural" head varies as the square of the velocity of the wind; and the ventilation produced by it, either directly or indirectly, varies as the velocity of the wind; the "thermal" head is proportional to the difference of the temperatures within and without the shaft; the "mechanical" head depends upon the machine

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* See a table in Stevenson and Murphy, Hygiene, Vol. i., page 84.

employed; with rotating fans it is proportional to the square of the velocity of the tips of the vanes.

What I wish now specially to point out with regard to this matter is that, if the head be compared with the flow it produces, it will be found that it is numerically proportional to the square of the flow for any simple ventilation circuit. The ratio is proportional to what may be called the combined resistance of the inlets and outlets, depending upon the shape and size of those areas. Work is spent in getting a cubic foot of air into a room and out of it again in many different ways; velocity has to be generated, corners have to be turned, bends rounded. It appears, from experiments into which I will not now enter, that all these demands upon the energy required for the passage of a single cubic foot of air are proportional to the square of the rate of travel of the cubic foot, and not to the simple current. In fact, the only item in the expenditure of energy which is simply proportional to the velocity is the friction in a long tube, and this, generally speaking, contributes only a small part to the whole resistance of the circuit.

I have verified by careful experiments upon a chimney that the law of proportion of head to the square of flow is very closely accurate. It follows—and this is the point at which I want to arrive—that the power required for a certain flow is proportional to the cube of the flow, and the conclusion to which I wish to draw special attention is that, under these circumstances, it is the resistance of the circuit, depending upon the magnitude of inlets and outlets, that is the critical factor in ventilation. It is useless to attempt to compensate for small inlets and outlets by more energetic machinery. Let me give some examples. Suppose you have an arrangement of inlets and outlets which, with a certain horse-power, affords ventilation for 100 persons, and you desire to accommodate 200 persons. To do so without altering the inlets and outlets would involve eightfold expenditure of horse-power. Or, again, a room with a fire in it will accommodate five persons comfortably, the fire supplying motive power for the necessary ventilation. If you put ten persons into the room and leave the inlets and outlets as they were, you ought to double the flow to accommodate the additional persons. It might be thought that you could get the extra flow by making up a more vigorous fire. It would require eight times the fire to secure the object, and perhaps I cannot more conclusively illustrate the dominant influence of the size of openings upon ventilation than by asking you to imagine the result of attempting to increase a fire to eight times its original size for the sake of accommodating five additional persons.

I have been asked to say something with special reference to the provision of ventilation in buildings already existing;

and I desire to say particularly this, that for the ventilation of any building, existing or non-existing, you must have adequate holes for the air to come in by and go out by. No mechanical contrivance can make up for the want of sufficient inlets and outlets. You may consider afterwards whether what comes in or goes out is precisely what you want, or do not want, as regards temperature and other matters, but do not attempt to make up by increased motive power for the want of area in inlets and outlets.

I should like to say a word or two about the casual openings that constitute the only source of air for ventilation in many inhabited rooms. It was an unfortunate day for ventilation when Pettenkofer succeeded in blowing out a candle by means of air driven through a brick. It is an interesting experiment, but it is not safe to draw from it the conclusion that provided the walls of your house are of brick no further provision for ventilation is needed, and yet implicitly this conclusion has been the basis of a good deal of action or of inaction in the matter of ventilation.

Casual openings of many kinds make up for the want of effective porosity of brick walls covered with plaster and wall-paper. Chinks in windows, doors, and floors all let in a certain amount of air to a room that has a fire to produce sufficient head for ventilation. I should estimate that sufficient air for three, or perhaps four persons, would be found to come in that way. If more than four persons are in a room the casual openings are no longer sufficient. Hence the arrangement that is good enough for a single bed-room, a study, or a sitting-room for three or four persons, is not adequate for a school class-room. In such a case you must count the persons to be supplied with air, and make the provision that you consider necessary to supply them. The chinks and casual openings become negligible in comparison with the special openings required, as soon as the number of occupants of a room becomes more than at the rate of, say, one per hundred square feet.

II.—Transmission of Power.

The second special consideration to which I desire to draw attention is more particularly applicable in the case of mechanical ventilation. It is this,—that one of the items of expenditure of energy in driving air through shafts is the actual production of velocity. My hearers will remember kinetic energy as one of the forms of energy, and the production of kinetic energy in ventilation currents is an important consideration. With ordinary arrangements for ventilation, kinetic energy is produced in the inlets and in the outlets, which are very narrow apertures compared with the dimensions of the room to be ventilated. If

the head for ventilation is produced by a single agent—a fan or a chimney—this is generally placed in one of the narrow channels. The energy necessary to get up the velocity in the second channel has to be "transmitted" from the source of power, the fan or chimney as the case may be. Now there are special considerations attaching to this pneumatic transmission of power; for one thing, it is transmitted to all openings, whether intended for the purpose or not; and, secondly, the low pressure fans in general use for ventilation purposes, are very uneconomical agents for transmitting energy; a good deal of power is apt to go to waste in the attempt. I conclude from this that where it is necessary to have considerable velocity in two separate portions of an air circuit, as in inlets and in outlets, it is better to have also separate means of producing the velocity. For producing velocity in outlets, chimneys as well as fans are available: for producing velocity in inlets without transmission of power, chimneys are not available; hot air may be so in a few special cases, but as a rule a fan is the only resource. A special advantage of avoiding the pneumatic transmission of power here spoken of, is that the air pressure in the room itself need not be either above or below that of the outside, so that open windows or doors need not disturb the regular course of the ventilation. This is a very important matter.

III.—Thermal Convection.

The third point to which I wish to direct your attention is concerned with the admission of air to a room, and its relation to the temperature of the room. I think the tendency, or rather the determination, of warm air to rise to the ceiling, and cold air to sink to the floor, is only imperfectly realised, as a rule. A few experiments would convince you that if you admit cold air to a room you may seek it successfully at the floor, no matter where you put your inlets; if, on the other hand, your air is admitted warm—warmer than the air already in the room—you must get a step-ladder if you want to find it. No mechanical arrangements that I know of will induce relatively warm air to reach persons near the floor until it has exhausted all the possibilities open to it at the ceiling; and, on the other hand, no arrangement of Tobin tubes or fine jets will induce cold air to float in warmer air for the benefit of the occupants of the room. The wonderful persistence with which cold air in crowded churches manages to reach one's feet—hidden away inaccessible to everything but cold air—is a striking indication of the inexorable laws of convection. Many important consequences follow from the recognition of these facts. To introduce warm air for the purposes of ventilation in a room

lighted with gas is to waste it. It makes its way forthwith to the upper part of the room, which the gas fumes have appropriated for their own uses. If, however, there is no gas, and warm air is introduced, it is desirable not to let it escape until it has come down to the level of the people who are to breathe it, otherwise its purpose fails. Hence, in a system of ventilation and warming which depends on warmed air, the extraction openings should be near the floor.

IV.—Quantity of Air Required.

I have still another point to put before you for special consideration. It is concerned with the amount of air necessary for efficient ventilation. You will know that the amount has been set at about a cubic foot per second, or somewhat less, for each person, and that that is regarded as an extravagant and impracticable amount by most practical ventilators. It is arrived at by a consideration of the amount of air necessary to dilute the carbonic acid, which is taken to be an index of the impurity. I have recently had to consider the matter from another point of view—that of temperature. In many cases you may notice that the effect upon temperature of the persons present in a room is unimportant, because the loss of heat through walls and windows is a most conspicuous factor; but in such places as your school chapels, where the number of persons present is very large compared with the cooling surface, the change of temperature during occupation is a very good index of the efficiency or inefficiency of the ventilation. I have calculated the rise of temperature which an adult person would cause in 3,000 cubic feet supplied to him in one hour, on account of his own combustion, and I find it to be about 5° F. You will probably agree with me that a properly warmed and ventilated chapel ought not to vary in temperature by more than 5° F. during occupation—say, from 58° F. to 63° F.—and I can commend to your notice for the purpose of examining your chapel arrangements a self-recording thermometer. I think you may find that unless you make the liberal allowance of 3,000 cubic feet per hour for each of the congregation you will get a greater rise in temperature than 5° in the hour, as well as too much carbonic acid.

V.—Ventilation as a Dynamical Problem.

I now propose to turn to the consideration of the general problem of ventilation. Ventilation problems are dynamical problems, but in some respects they are so closely analogous to corresponding electrical problems, that I may be pardoned

for drawing attention to the analogy; you will find it of immense assistance in all practical applications.

The analogy can be built up from the simplest examples. A simple electrical circuit consists of a battery, which has an electromotive force and resistance, external resistance and connecting wires. A simple ventilation circuit (for a single room) consists of the moving agent (*e.g.*, a chimney and fire), which has aëromotive force and resistance, external resistance (the resistance of inlets) and connecting spaces (the room and the external air).

A second independent ventilation circuit (for a second room) can in like manner be resolved into a second aëromotive force, resistance and connecting spaces, and be represented by a second electric circuit with its electromotive force, resistances and connecting wires. The two ventilation circuits are connected because one of the analogues of connecting wires—the external air—is common to both circuits. If the rooms are adjoining rooms with a door between them they have a second connexion.

The law of relation between aëromotive force, flow and resistance, $A = V^2 R$, is different from the electrical law (Ohm's law), $E = C R$, in that the pneumatic flow (V) enters as a squared quantity, while the electric current (C) enters in the first power; but otherwise the analogy can be followed to any of its consequences.

If we work out the analogy for a house of several floors, we get a very complicated and intricate problem; aëromotive forces exist wherever there are fires, wherever there are openings exposed to wind, and wherever there are fans. There are also subsidiary aëromotive forces between rooms on different floors, owing to differences of temperature between the inside and outside of the house. Resistances exist for all channels of entry, ventilation openings, window or door openings, chinks, "cold" open chimneys, &c., and for all channels of exit. In an ordinary house the latter are generally limited to the chimneys that have fires in their grates, unless there are openings on opposite sides and wind enough to make use of them; but, just as, with a complicated electrical network, we can follow along with the current all round a complete circuit, and taken the sum of the products of current and resistance to be equal to the algebraic sum of all the electromotive forces in the circuit; so we can follow along the ventilation circuit into the building by any practicable path and out again, and take the sum of the products of the resistance and the square of the flow in each part to be equal to the algebraic sum of the aëromotive forces; or, in other words, to the effective "head" for that circuit.

The complication thus indicated when a building of many

rooms is dealt with is somewhat appalling. So is the corresponding complication of the electrical analogy ; but it is the complication which exists in nature, and it is merely burying one's head in the sand to act as though the ventilation of a building were a simple pneumatic problem.

As compared with the electrical problem, the pneumatic or ventilation problem, is still further complicated by the necessity for considering "draughts," or the distribution of air in the connecting spaces, whereas in electrical problems the distribution of currents in the connecting wires need not be considered. Even without this additional complication, I doubt if anyone would attempt to determine practically the distribution of currents in so complicated a network ; but, in those cases, electricians do not shut their eyes to two-thirds of the elements that have to be considered, and say the remainder affords a practicable problem ; they would reduce the conditions, and insulate the circuits until the necessary simplicity was realised. Progress in ventilation will not be really effective until a corresponding plan is adopted for the pneumatic problems.

Let me briefly classify the systems of ventilation from the point of view of the electrical analogy.

There is the "natural" system, depending on more or less simple openings for inlets and outlets, and upon wind for aëromotive force. I confess to not knowing enough about the wind to be able to go far into numerical calculations with this system. I have made some attempt in a Report on the Dormitories of Poor Law Schools ; but it is inevitably based on averages with which individual cases do not necessarily correspond.

The plenum system provides a single dominant aëromotive force in one inlet. It achieves comparative simplicity by closing as far as possible all openings except those intended by the ventilating engineer for his own use.

The vacuum system, on the contrary, puts the single dominant aëromotive force in the outlet, and takes in air from various sources, casual or otherwise. The effective reduction to a simple form is not nearly so complete as with the plenum system.

In passing it may be useful to remark that the happy-go-lucky system of the ordinary London house is not by any means so bad or unscientific as might be supposed. In this case the aëromotive force arises from fires in grates at the foot of chimneys which form the outlets. The inlets, when they are not open windows, are casual ; they include too many openings in the basement, which supply air primarily to the kitchen department, to be carried up to the fires above stairs mixed with the smell of cooking. But the inlets also include the cold flues, and I think it will be found that in many cases

the cold flues afford the most effective and permanent air supply of a house when the windows and basement door are closed.

This mode of supply has many advantages. It takes the air from above the roof, where it is free from the impurities of the streets. It is true that the opening from which the air is drawn is perilously near the openings of chimneys which are delivering smoke, and that in times of fog there is a good deal of smoke mixed with the air. But, on the other hand, the occasional fire in the grate at the foot of the chimney purifies the air channel even more effectively than dusting out a channel exclusively reserved for inlet purposes, and the layer of soot may act also to some extent as a disinfectant. Moreover, the flues are all in the party walls, and the cold flue is probably between two, or at least adjoins one that carries away the smoke of an active fire, so that the incoming air is moderately warmed by the time it gets into the rooms. With an allowance of two cold flues to one active fire a very reasonable system of ventilation would be maintained, sufficient in the aggregate for, say, three persons per fire—a moderate estimate for a London household.

VI.—Draughts.

As already mentioned, the treatment of ventilation problems by the electrical analogy omits a very important aspect of the question, namely, the distribution of currents in the ventilated space. This is the much discussed question of draughts. In speaking of a discussion upon ventilation at the Sanitary Institute last year, a prominent sanitary authority remarked to me that no one of the speakers had defined a draught. I am going to attempt a definition ; you may take it for what it is worth. I will define it as the perception of cold air in a vitiated atmosphere. I desire by the wording of the definition to indicate collaterally, first, that a draught is partly a subjective phenomenon—one man's draught is another man's fresh air—and, secondly, that in the open and fresh air, draughts properly so called do not exist. To avoid draughts, therefore, *keep* the air fresh, and if you do not avoid all the evil consequences you will avoid some ; but do not arrange matters so that the atmosphere first becomes seriously vitiated and then partially replaced by cold currents. You would then get a real draught. I am not a physiologist, and I do not understand these matters, but I imagine it possible that the human organism, in arranging things to contend with the poison of vitiated air, makes a certain disposition of its forces, and in arranging things to face the cold, adopts another disposition ; and further, that when you ask it to adopt both dis-

positions at the same time you demand too much, and the consequences are disastrous.

Draughts are of two kinds : one is due to the actual entrance of streams of cold air into a room, and the other is due to the formation of streams of cold air in the interior of a building by the cooling effect of window surfaces, when the outside air is very cold compared with the interior. There is no way of preventing the first without restricting the ventilation, except by warming the incoming air. I have already spoken of the relation of the temperature of air to its distribution on entering a room. Draughts of the second kind are much more pernicious, because the air remains vitiated in spite of them. I could give you some conspicuous instances of them, particularly in certain places of worship ; the condensation of moisture on the windows of a crowded room affords ample evidence of the transmission of enormous quantities of heat, which must produce dynamical effects. I should like to see these removed by catching the cold air as it descends along the windows and removing it from the building by extraction openings under them ; but if this cannot be, warming arrangements under the windows can be made to compensate for the loss of heat, and the dynamical effects can thus be avoided.

VII.—Examination of Arrangements for Ventilation.

I turn next to the consideration of the mode of examining the ventilation of a building either actually constructed or in plan. This is a comparatively simple matter. Taking each room in turn, consider what are—for that room—(1) the inlets, (2) the outlets, (3) the motive power, in summer and in winter. It will generally be found that the motive power is restricted to the inlets or the outlets, generally to a single channel. In that case the correct action of other openings originally intended for the same purpose is less than doubtful. Having identified the motive power, it is next important to ascertain the volume of the ventilation currents as measured either in the inlets or outlets. Then the temperature of the entering air and its quality should be examined.

These items can all be very rapidly determined. For example, if a school class-room has a single fire, no special opening except windows and a door to a corridor, you may take the fire as requiring from 10,000 to 15,000 cubic feet of air per hour. This comes either from the windows, the corridor, or the chinks, and an estimate of the temperature and of the quality of the air coming in is then easily made. One open fire for five or six boys without any other provision might give tolerable ventilation. If you find a single open fire ventilating a class-room for

twenty boys, you have still something to think about in the matter of ventilation.

VIII.—Details.

With this mode of examining and tabulating ventilation requirements in view, I may now refer to a few points in regard to the different types of rooms that you have to deal with.

For dormitories I must confess that the causes which make for the mixing of air are so many and so vigorous that from the point of view of effective isolation separate rooms for the boys with separate inlets and outlets are unavoidable *desiderata*. This may be a counsel of perfection, and the advantages of isolation may have to go in consideration of other matters, but if not a separate room for each boy, then as few boys as possible in each room is a clear necessity. I should like to suggest an experiment in this matter for your consideration. Set your dormitory ventilation at its best and light a pastille, or place some evil smelling compound in the dormitory—the boys will suggest one if you are unable to do so—and ascertain whether your ventilation arrangements prevent the smell diffusing over the room.

I will add a word as to closets; it is usual to leave them cold and trust to open windows for their ventilation. They nearly always act as inlets to the adjoining buildings. The obvious plan is to make them the locus of vigorous extraction shafts, and as you remove certain waste products in one direction remove the air in another. Let these outlets be fed by air from the passages so that the direction of flow is from the building to the outlets in the closets, and not the reverse. For some reason or other it has generally been regarded as necessary to put apparatus for extracting air into immediate connexion with the room to be ventilated. In consequence the room is apt to become the receptacle for all the specimens of air that have nowhere in particular to go to, and the air which finds its way into closets is one of these specimens. The extraction apparatus might be quite as effectively employed for its purpose if the closet formed the lower portion of the extraction arrangement.

In the ventilation of chapels you have quite an open field. I am acquainted with one church which has a most amusing provision for ventilation. To the best of my recollection it consists of eight 3-inch square openings in the sills of the windows, four on each side, communicating with 9-inch airbricks outside, several feet below. With an unusually strong wind, if the channels are not blocked with builders' rubbish, one of these openings might deliver air for a single person. In all, a congregation of four persons is provided for; but if anyone complains that a congregation of two hundred find it

impossible to stay out the service, the special provision for ventilation is pointed to in triumphant vindication of the careful foresight of the designers. No church that I am acquainted with has really attempted to provide air for its congregation. The aëromotive force is derived from the difference of temperature within and without the building, or from wind ; the inlets are such doors or windows as happen to be open—chinks do not count where a large congregation is concerned—the outlets are whatever the air can find in the roof or the upper windows. If you can give school chapels their due in the matter of fresh air you will initiate a new and most valuable departure in ventilation.

As for studies, if a study has a fireplace, and a fire in it, you may rely upon its being ventilated for four persons or thereabout. If it has no fire it would be well to consider what the aëromotive force is which produces ventilation. If the heating is by hot water the amount of opening required to ensure an adequate supply of air is so large that we approach the open-air system.

I have not dealt with this system. I have supposed it not strictly included among systems of ventilation. It may, after all, be the proper plan to adopt ; but, regarding the matter purely from the point of view of history, without any scientific refinements, I suppose our ancestors tried it, and preferred tuberculosis. They may have been unwise.